Incremental Semantic Dependency Parsing

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Introduction: Motivation

The person who officials say ___ stole millions . . .

Introduction: Motivation

The person who officials say ___ stole millions . . .

Goal: Incrementally obtain correct parse

- Filler-gap is hard for computers
  [Rimell et al., 2009, Nguyen et al., 2012]

Introduction: Motivation

The person who officials say ___ stole millions . . .

Goal: Test human processing claims

- Filler-gap is hard for humans? [Chomsky and Miller, 1963]

Introduction: Motivation

The person who officials say ___ stole millions ...

Goal: Test human processing claims

- Filler-gap is hard for humans [Gibson, 2000, Chen et al., 2005]

Introduction: Motivation

The person who officials say ___ stole millions . . .

Goal: Test human processing claims

- Filler-gap is hard for humans [Gibson, 2000, Chen et al., 2005]
- Embeddings speed processing [Pynte et al., 2008]
- Finishing embeddings = Fast
  [Wu et al., 2010, van Schijndel and Schuler, 2013]

Center embedding or filler-gap?

Overview

Contribution

Introduce an incremental semantic parser

- Fits reading times better than syntax parsing
- Replicate previous findings sans surface confounds

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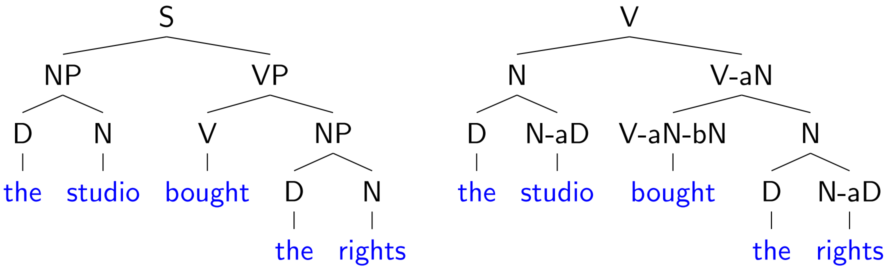
1. Generalized Categorial Grammar
2. Incremental Semantic Parser
3. Eye-tracking evaluation
4. Results

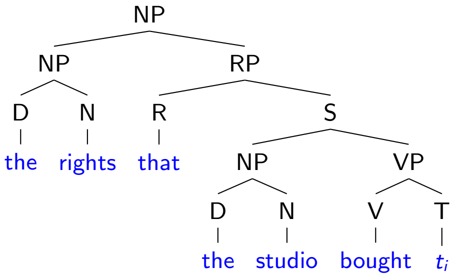
Generalized Categorial Grammar

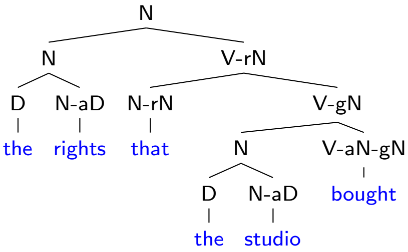
Reannotate WSJ [Nguyen et al., 2012]



Generalized Categorial Grammar

We can also keep the WSJ traces around.





Interpretation: Reannotation Rules

$$\frac{g{:}d \quad h{:}\, c\text{-}\mathbf{a}d}{(f_{c\text{-}\mathbf{a}d}\; g\; h){:}\, c} \qquad \frac{g{:}d\psi \quad h{:}\, c\text{-}\mathbf{a}d}{\lambda_k\, (f_{c\text{-}\mathbf{a}d}\; (g\; k)\; h){:}\, c\psi} \qquad \frac{g{:}d \quad h{:}\, c\text{-}\mathbf{a}d\psi}{\lambda_k\, (f_{c\text{-}\mathbf{a}d}\; g\; (h\; k)){:}\, c\psi} \qquad \frac{g{:}d\psi \quad h{:}\, c\text{-}\mathbf{a}d\psi}{\lambda_k\, (f_{c\text{-}\mathbf{a}d}\; (g\; k)\; (h\; k)){:}\, c\psi}$$

$$\frac{g{:}\, c\text{-}\mathbf{b}d \quad h{:}d}{(f_{c\text{-}\mathbf{b}d}\; g\; h){:}\, c} \qquad \frac{g{:}\, c\text{-}\mathbf{b}d\psi \quad h{:}d}{\lambda_k\, (f_{c\text{-}\mathbf{b}d}\; (g\; k)\; h){:}\, c\psi} \qquad \frac{g{:}\, c\text{-}\mathbf{b}d \quad h{:}d\psi}{\lambda_k\, (f_{c\text{-}\mathbf{b}d}\; g\; (h\; k)){:}\, c\psi} \qquad \frac{g{:}\, c\text{-}\mathbf{b}d\psi \quad h{:}d\psi}{\lambda_k\, (f_{c\text{-}\mathbf{b}d}\; (g\; k)\; (h\; k)){:}\, c\psi}$$

(Aa–h)

$$\frac{g{:}\, u\text{-}\mathbf{a}d \quad h{:}c}{(f_{\mathrm{IM}}\; g\; h){:}c} \qquad \frac{g{:}\, u\text{-}\mathbf{a}d\psi \quad h{:}c}{\lambda_k\, (f_{\mathrm{IM}}\; (g\; k)\; h){:}c\psi} \qquad \frac{g{:}\, u\text{-}\mathbf{a}d \quad h{:}c\psi}{\lambda_k\, (f_{\mathrm{IM}}\; g\; (h\; k)){:}c\psi} \qquad \frac{g{:}\, u\text{-}\mathbf{a}d\psi \quad h{:}c\psi}{\lambda_k\, (f_{\mathrm{IM}}\; (g\; k)\; (h\; k)){:}c\psi}$$

$$\frac{g{:}c \quad h{:}\, u\text{-}\mathbf{a}d}{(f_{\mathrm{FM}}\; g\; h){:}c} \qquad \frac{g{:}c\psi \quad h{:}\, u\text{-}\mathbf{a}d}{\lambda_k\, (f_{\mathrm{FM}}\; (g\; k)\; h){:}c\psi} \qquad \frac{g{:}c \quad h{:}\, u\text{-}\mathbf{a}d\psi}{\lambda_k\, (f_{\mathrm{FM}}\; g\; (h\; k)){:}c\psi} \qquad \frac{g{:}c\psi \quad h{:}\, u\text{-}\mathbf{a}d\psi}{\lambda_k\, (f_{\mathrm{FM}}\; (g\; k)\; (h\; k)){:}c\psi}$$

(Ma–h)

$$\frac{g{:}\, c\text{-}\mathbf{a}d}{\lambda_k\, (f_{c\text{-}\mathbf{a}d}\; \{k\}\; g){:}\, c\text{-}\mathbf{g}d} \qquad \frac{g{:}\, c\text{-}\mathbf{b}d}{\lambda_k\, (f_{c\text{-}\mathbf{a}d}\; \{k\}\; g){:}\, c\text{-}\mathbf{g}d} \qquad \frac{g{:}c}{\lambda_k\, (f_{\mathrm{IM}}\; \{k\}\; g){:}c\text{-}\mathbf{g}d}$$

(Ga–c)

$$\frac{g{:}e \quad h{:}\, c\text{-}\mathbf{g}d}{\lambda_i\, \exists_j\, (g\; i) \wedge (h\; i\; j){:}e} \qquad \frac{g{:}d\text{-}\mathbf{r}e \quad h{:}\, c\text{-}\mathbf{g}d}{\lambda_{k\,j}\, \exists_i\, (g\; k\; i) \wedge (h\; i\; j){:}\, c\text{-}\mathbf{r}e} \qquad \frac{g{:}d\text{-}\mathbf{i}e \quad h{:}\, c\text{-}\mathbf{g}d}{\lambda_{k\,j}\, \exists_i\, (g\; k\; i) \wedge (h\; i\; j){:}\, c\text{-}\mathbf{i}e}$$

(Fa–c)

$$\frac{g{:}e \quad h{:}c\text{-}\mathbf{r}d}{\lambda_i\, \exists_j\, (g\; i) \wedge (h\; i\; j){:}e}$$

(R)

Interpretation: Reannotation Rules

$$\frac{g{:}d \quad h{:}\,c\text{-}\mathbf{a}d}{(f_{c\text{-}\mathbf{ad}}\, g\, h){:}\, c} \qquad \frac{g{:}d\psi \quad h{:}\,c\text{-}\mathbf{a}d}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,(g\,k)\,h){:}\,c\psi} \qquad \frac{g{:}d \quad h{:}\,c\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,g\,(h\,k)){:}\,c\psi} \qquad \frac{g{:}d\psi \quad h{:}\,c\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,(g\,k)\,(h\,k)){:}\,c\psi}$$

$$\frac{g{:}\,c\text{-}\mathbf{b}d \quad h{:}d}{(f_{c\text{-}\mathbf{bd}}\, g\, h){:}\, c} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d\psi \quad h{:}d}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,(g\,k)\,h){:}\,c\psi} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d \quad h{:}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,g\,(h\,k)){:}\,c\psi} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d\psi \quad h{:}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,(g\,k)\,(h\,k)){:}\,c\psi}$$

(Aa–h)

$$\frac{g{:}\,u\text{-}\mathbf{a}d \quad h{:}c}{(f_{\mathrm{IM}}\, g\, h){:}c} \qquad \frac{g{:}\,u\text{-}\mathbf{a}d\psi \quad h{:}c}{\lambda_k\,(f_{\mathrm{IM}}\,(g\,k)\,h){:}c\psi} \qquad \frac{g{:}\,u\text{-}\mathbf{a}d \quad h{:}c\psi}{\lambda_k\,(f_{\mathrm{IM}}\,g\,(h\,k)){:}c\psi} \qquad \frac{g{:}\,u\text{-}\mathbf{a}d\psi \quad h{:}c\psi}{\lambda_k\,(f_{\mathrm{IM}}\,(g\,k)\,(h\,k)){:}c\psi}$$

$$\frac{g{:}c \quad h{:}\,u\text{-}\mathbf{a}d}{(f_{\mathrm{FM}}\, g\, h){:}c} \qquad \frac{g{:}c\psi \quad h{:}\,u\text{-}\mathbf{a}d}{\lambda_k\,(f_{\mathrm{FM}}\,(g\,k)\,h){:}c\psi} \qquad \frac{g{:}c \quad h{:}\,u\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{\mathrm{FM}}\,g\,(h\,k)){:}c\psi} \qquad \frac{g{:}c\psi \quad h{:}\,u\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{\mathrm{FM}}\,(g\,k)\,(h\,k)){:}c\psi}$$

(Ma–h)

$$\frac{g{:}\,c\text{-}\mathbf{a}d}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,\{k\}\;g){:}\,c\text{-}\mathbf{g}d} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d}{\lambda_k\,(f_{c\text{-}\mathbf{ad}}\,\{k\}\;g){:}\,c\text{-}\mathbf{g}d} \qquad \frac{g{:}c}{\lambda_k\,(f_{\mathrm{IM}}\,\{k\}\;g){:}c\text{-}\mathbf{g}d}$$

(Ga–c)

$$\frac{g{:}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_i\,\exists_j\,(g\;i) \wedge (h\;i\;j){:}e} \qquad \frac{g{:}d\text{-}\mathbf{r}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_{k\,j}\,\exists_i\,(g\;k\;i) \wedge (h\;i\;j){:}\,c\text{-}\mathbf{r}e} \qquad \frac{g{:}d\text{-}\mathbf{i}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_{k\,j}\,\exists_i\,(g\;k\;i) \wedge (h\;i\;j){:}\,c\text{-}\mathbf{i}e}$$

(Fa–c)

$$\frac{g{:}e \quad h{:}c\text{-}\mathbf{r}d}{\lambda_i\,\exists_j\,(g\;i) \wedge (h\;i\;j){:}e} \qquad \text{(R)}$$

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$$\frac{g{:}\,c\text{-}\mathbf{b}d \quad h{:}d}{(f_{c\text{-}\mathbf{bd}}\; g\; h){:}\,c} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d\psi \quad h{:}d}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,(g\;k)\;h){:}\,c\psi} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d \quad h{:}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\;g\;(h\;k)){:}\,c\psi} \qquad \frac{g{:}\,c\text{-}\mathbf{b}d\psi \quad h{:}d\psi}{\lambda_k\,(f_{c\text{-}\mathbf{bd}}\,(g\;k)\;(h\;k)){:}\,c\psi}$$

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$$\frac{g{:}c \quad h{:}\,u\text{-}\mathbf{a}d}{(f_{\mathrm{FM}}\; g\; h){:}c} \qquad \frac{g{:}c\psi \quad h{:}\,u\text{-}\mathbf{a}d}{\lambda_k\,(f_{\mathrm{FM}}\,(g\;k)\;h){:}c\psi} \qquad \frac{g{:}c \quad h{:}\,u\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{\mathrm{FM}}\;g\;(h\;k)){:}c\psi} \qquad \frac{g{:}c\psi \quad h{:}\,u\text{-}\mathbf{a}d\psi}{\lambda_k\,(f_{\mathrm{FM}}\,(g\;k)\;(h\;k)){:}c\psi}$$

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$$\frac{g{:}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_i\,\exists_j\,(g\;i)\wedge(h\;i\;j){:}e} \qquad \frac{g{:}d\text{-}\mathbf{r}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_{k\,j}\,\exists_i\,(g\;k\;i)\wedge(h\;i\;j){:}\,c\text{-}\mathbf{r}e} \qquad \frac{g{:}d\text{-}\mathbf{i}e \quad h{:}\,c\text{-}\mathbf{g}d}{\lambda_{k\,j}\,\exists_i\,(g\;k\;i)\wedge(h\;i\;j){:}\,c\text{-}\mathbf{i}e}$$

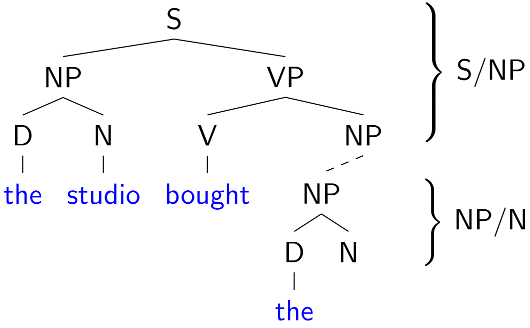
(Fa–c)

$$\frac{g{:}e \quad h{:}c\text{-}\mathbf{r}d}{\lambda_i\,\exists_j\,(g\;i)\wedge(h\;i\;j){:}e}$$

(R)

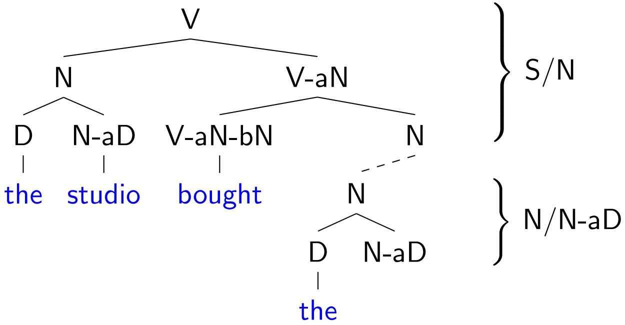
Interpretation

Connected Components

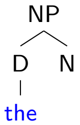


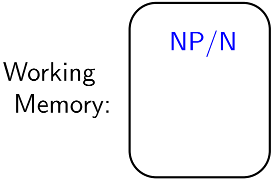
Interpretation

Reannotated Connected Components

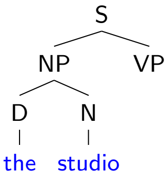


Connected Component Parsing

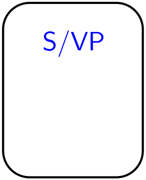




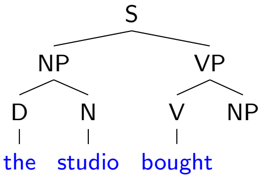
Connected Component Parsing

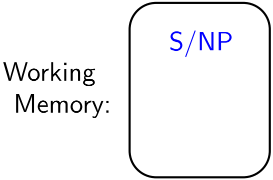


Working Memory:

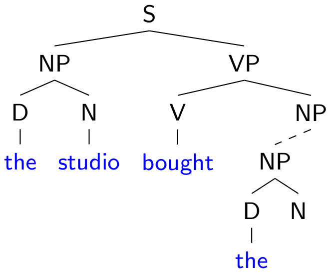


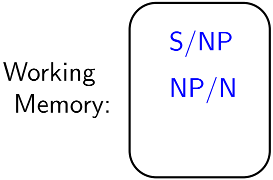
Connected Component Parsing



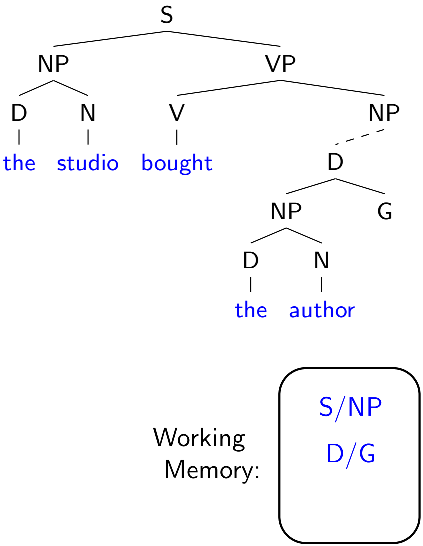


Connected Component Parsing

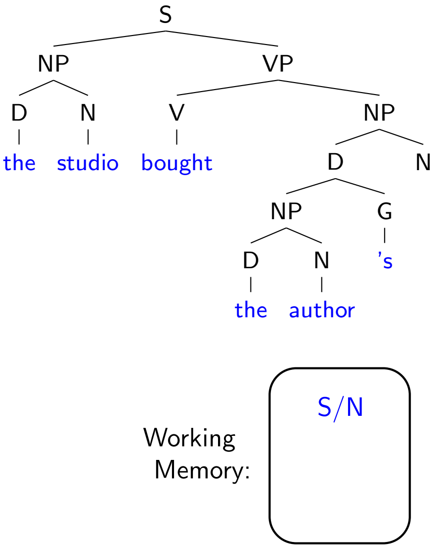




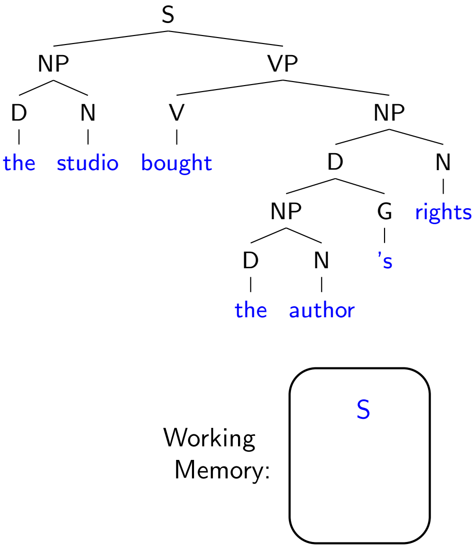
Connected Component Parsing



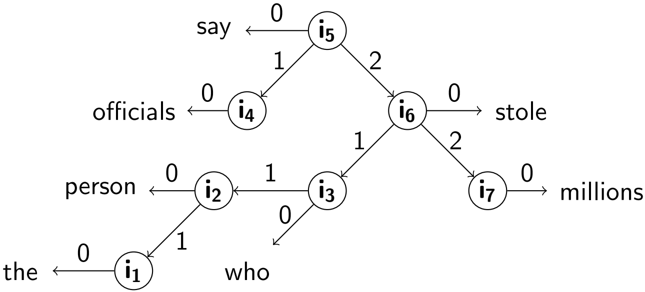
Connected Component Parsing



Connected Component Parsing



Interpretation: Referent States



Interpretation: Fa/La

First or Last element of a CC

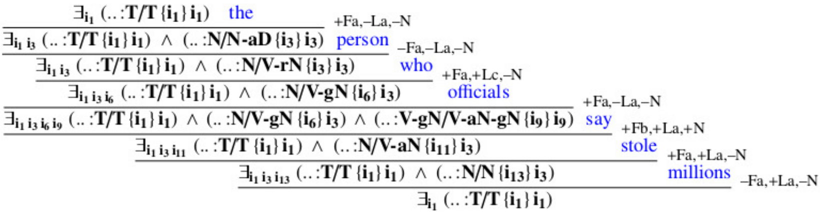
$$\frac{\exists_{i^1 j^1 .. i^\ell j^\ell} \; \ldots \; \wedge \; (g^\ell{:}c/d\,\{j^\ell\}\; i^\ell) \quad x_t}{\exists_{i^1 j^1 .. i^\ell} \; \ldots \; \wedge \; ((g^\ell f){:}c\; i^\ell)} \; x_t \mapsto_M f{:}d \qquad (-\text{Fa})$$

$$\frac{\exists_{i^1 j^1 .. i^\ell j^\ell} \; \ldots \; \wedge \; (g^\ell{:}c/d\,\{j^\ell\}\; i^\ell) \quad x_t}{\exists_{i^1 j^1 .. i^\ell j^\ell i^{\ell+1}} \; \ldots \; \wedge \; (g^\ell{:}c/d\,\{j^\ell\}\; i^\ell) \; \wedge \; (f{:}e\; i^{\ell+1})} \; x_t \mapsto_M f{:}e \qquad (+\text{Fa})$$

$$\frac{\exists_{i^1 j^1 .. i^{\ell-1} j^{\ell-1} i^\ell} \; \ldots \; \wedge \; (g^\ell{:}d\; i^\ell)}{\exists_{i^1 j^1 .. i^\ell j^\ell} \; \ldots \; \wedge \; ((f g^\ell){:}c/e\,\{j^\ell\}\; i^\ell)} \begin{cases} g{:}d \;\; h{:}e \Rightarrow (f\; g\; h){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k (f\; (g\; k)\; h){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k (f\; g\; (h\; k)){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k (f\; (g\; k)\; (h\; k)){:}c \end{cases} \qquad (-\text{La})$$

$$\frac{\exists_{i^1 j^1 .. i^{\ell-1} j^{\ell-1} i^\ell} \; \ldots \; \wedge \; (g^{\ell-1}{:}a/c\,\{j^{\ell-1}\}\; i^{\ell-1}) \; \wedge \; (g^\ell{:}d\; i^\ell)}{\exists_{i^1 j^1 .. i^{\ell-1} j^{\ell-1}} \; \ldots \; \wedge \; (g^{\ell-1} \circ (f\; g^\ell){:}a/e\,\{j^{\ell-1}\}\; i^{\ell-1})} \begin{cases} g{:}d \;\; h{:}e \Rightarrow (f\; g\; h){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k (f\; (g\; k)\; h){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k (f\; g\; (h\; k)){:}c \\ g{:}d \;\; h{:}e \Rightarrow \lambda_k (f\; (g\; k)\; (h\; k)){:}c \end{cases} \qquad (+\text{La})$$

Interpretation



Interpretation: Fb/Lb

$$\psi \in \{\text{-r,-i}\} \times \text{C}$$

$$\frac{\exists_{i^1 j^1 .. i^n j^n .. i^\ell j^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^\ell{:}c/d\,\{j^\ell\}\,i^\ell) \quad x_t}{\exists_{i^1 j^1 .. i^n j^n .. i^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge ((g^\ell(f'\{j^n\} f)){:}c\,i^\ell)}$$

$$x_t \mapsto_M \lambda_k(f'\{k\}\,f){:}d \quad (\text{–Fb})$$

$$\frac{\exists_{i^1 j^1 .. i^n j^n .. i^\ell j^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^\ell{:}c/d\,\{j^\ell\}\,i^\ell) \quad x_t}{\exists_{i^1 j^1 .. i^n j^n .. i^\ell j^\ell i^{\ell+1}} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^\ell{:}c/d\,\{j^\ell\}\,i^\ell) \wedge ((f'\{j^n\} f){:}e\,i^{\ell+1})}$$

$$x_t \mapsto_M \lambda_k(f'\{k\}\,f){:}e \quad (+\text{Fb})$$

$$\frac{\exists_{i^1 j^1 .. i^n j^n .. i^{\ell-1} j^{\ell-1} i^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^\ell{:}d\,i^\ell)}{\exists_{i^1 j^1 .. i^n j^n .. i^\ell j^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge ((fg^\ell) \circ (f'\{j^n\}){:}c\psi/e\,\{j^\ell\}\,i^\ell)}$$

$$g{:}d \;\; h{:}e \Rightarrow \lambda_k(fg\,(f'\{k\}\,h)){:}c\psi \quad (\text{–Lb})$$

$$\frac{\exists_{i^1 j^1 .. i^n j^n .. i^{\ell-1} j^{\ell-1} i^\ell} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^{\ell-1}{:}a/c\psi\,\{j^{\ell-1}\}\,i^{\ell-1}) \wedge (g^\ell{:}d\,i^\ell)}{\exists_{i^1 j^1 .. i^n j^n .. i^{\ell-1} j^{\ell-1}} \ldots \wedge (g^n{:}y/z\psi\,\{j^n\}\,i^n) \wedge \ldots \wedge (g^{\ell-1} \circ (fg^\ell) \circ (f'\{j^n\}){:}a/e\,\{j^{\ell-1}\}\,i^{\ell-1})}$$

$$g{:}d \;\; h{:}e \Rightarrow \lambda_k(fg\,(f'\{k\}\,h)){:}c\psi \quad (+\text{Lb})$$

Interpretation: Lc/N

$$\frac{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1} i^\ell} \; \ldots \; \wedge \; (g^\ell{:}d \; i^\ell)}{\exists_{i^1 j^1 .. \, i^\ell j^\ell} \; \ldots \; \wedge \; ((fg^\ell) \circ (\lambda_{h\,k\,i}\,(h\,k)){:}a/e\psi \,\{j^\ell\}\, i^\ell)} \quad g{:}d \;\; h{:}e\psi \Rightarrow (fg\;h){:}c \qquad (\text{–Lc})$$

$$\frac{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1} i^\ell} \; \ldots \; \wedge \; (g^{\ell-1}{:}a/c \,\{j^{\ell-1}\}\, i^{\ell-1}) \; \wedge \; (g^\ell{:}d \; i^\ell)}{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1}} \; \ldots \; \wedge \; (g^{\ell-1} \circ (fg^\ell) \circ (\lambda_{h\,k\,i}\,(h\,k)){:}a/e\psi \,\{j^{\ell-1}\}\, i^{\ell-1})} \quad g{:}d \;\; h{:}e\psi \Rightarrow (fg\;h){:}c \qquad (+\text{Lc})$$

$$\frac{\exists_{i^1 j^1 .. \, i^\ell j^\ell} \; \ldots \; \wedge \; (g^{\ell-1}{:}c/d\psi \,\{j^{\ell-1}\}\, i^{\ell-1}) \; \wedge \; (g^\ell{:}d\psi/e \,\{j^\ell\}\, i^\ell)}{\exists_{i^1 j^1 .. \, i^{\ell-1} j^{\ell-1}} \; \ldots \; \wedge \; (g^{\ell-1} \circ (\lambda_{h\,i} \exists_j (h\,j)) \circ g^\ell{:}c/e \,\{j^{\ell-1}\}\, i^{\ell-1})} \qquad (+\text{N})$$

All of these rules may be made probabilistic

Interpretation

$$\exists_{i_1}\ (..:\mathbf{T/T}\ \{\mathbf{i_1}\}\ \mathbf{i_1}) \quad \text{the} \quad {+}\text{Fa},{-}\text{La},{-}\text{N}$$

$$\exists_{i_1 i_3}\ (..:\mathbf{T/T}\ \{\mathbf{i_1}\}\ \mathbf{i_1}) \wedge (..:\mathbf{N/N\text{-}aD}\ \{\mathbf{i_3}\}\ \mathbf{i_3}) \quad \text{person} \quad {-}\text{Fa},{-}\text{La},{-}\text{N}$$

$$\exists_{i_1 i_3}\ (..:\mathbf{T/T}\ \{\mathbf{i_1}\}\ \mathbf{i_1}) \wedge (..:\mathbf{N/V\text{-}rN}\ \{\mathbf{i_3}\}\ \mathbf{i_3}) \quad \text{who} \quad {+}\text{Fa},{+}\text{Lc},{-}\text{N}$$

$$\exists_{i_1 i_3 i_6}\ (..:\mathbf{T/T}\ \{\mathbf{i_1}\}\ \mathbf{i_1}) \wedge (..:\mathbf{N/V\text{-}gN}\ \{\mathbf{i_6}\}\ \mathbf{i_3}) \quad \text{officials} \quad {+}\text{Fa},{-}\text{La},{-}\text{N}$$

$$\exists_{i_1 i_3 i_6 i_9}\ (..:\mathbf{T/T}\ \{\mathbf{i_1}\}\ \mathbf{i_1}) \wedge (..:\mathbf{N/V\text{-}gN}\ \{\mathbf{i_6}\}\ \mathbf{i_3}) \wedge (..:\mathbf{V\text{-}gN/V\text{-}aN\text{-}gN}\ \{\mathbf{i_9}\}\ \mathbf{i_9}) \quad \text{say} \quad {+}\text{Fb},{+}\text{La},{+}\text{N}$$

$$\exists_{i_1 i_3 i_{11}}\ (..:\mathbf{T/T}\ \{\mathbf{i_1}\}\ \mathbf{i_1}) \wedge (..:\mathbf{N/V\text{-}aN}\ \{\mathbf{i_{11}}\}\ \mathbf{i_3}) \quad \text{stole} \quad {+}\text{Fa},{+}\text{La},{-}\text{N}$$

$$\exists_{i_1 i_3 i_{13}}\ (..:\mathbf{T/T}\ \{\mathbf{i_1}\}\ \mathbf{i_1}) \wedge (..:\mathbf{N/N}\ \{\mathbf{i_{13}}\}\ \mathbf{i_3}) \quad \text{millions} \quad {-}\text{Fa},{+}\text{La},{-}\text{N}$$

$$\exists_{i_1}\ (..:\mathbf{T/T}\ \{\mathbf{i_1}\}\ \mathbf{i_1})$$

Evaluation: Syntactic vs Semantic

Syntactic Parser [van Schijndel et al., 2013]

- Only Fa/La
- Trained on WSJ 02-21
- Split-merged $\times 5$ [Petrov et al., 2006]

Semantic Parser

- Trained on Reannotated WSJ 02-21
- Split-merged $\times 3$

Evaluation: Syntactic vs Semantic

Test Corpus: Dundee

- Log-transformed go-past durations
- Omit:
  - first and last of each line (wrap-up)
  - $<$ 5 times in WSJ (accuracy) [Fossum and Levy, 2012]
  - saccade length $>$ 4 (track loss) [Demberg and Keller, 2008]

Eye Tracking

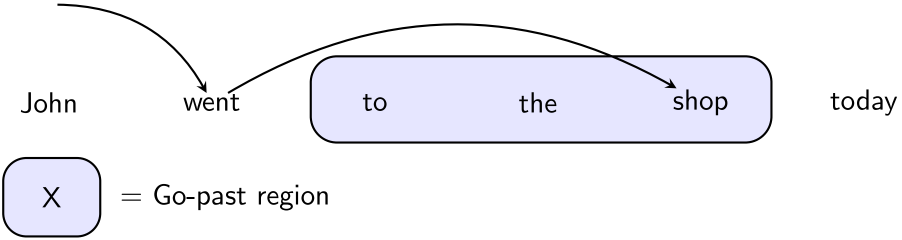
Go-past durations:

John went to the shop today

Cumulative factors are summed over the go-past region
Non-cumulative factors are based on the initial word in a region (shop)

Eye Tracking

Go-past durations:



= Go-past region

Cumulative factors are summed over the go-past region

Non-cumulative factors are based on the initial word in a region (shop)

Evaluation: Syntactic vs Semantic

Fitting a linear mixed effects model (*lmer* in R)

Fixed Effects

- Word length
- Sentence position
- Prev, Next word fixated?
- Unigram and bigram probs
- Surprisal [Hale, 2001]
- Region length
- Cum. surprisal
- Cum. entropy reduction [Hale, 2003]
- Joint interactions
- Spillover predictors

By-subject random slopes

- Region length
- Prev word fixated?
- Cumulative surprisal

Subject and Item random intercepts

Evaluation: Syntactic vs Semantic

Model	log-likelihood	AIC
syntactic	-64175	128619
semantic	-64169	128609

Goodness-of-fits

Relative likelihood: 0.0009 (n = 151,331)

Evaluation: Semantic Factors

Factor	coeff	std. err.	t-score	p-value
F+L– (encoding)	0.014	0.005	2.665	0.02
F–L+ (integration)	-0.021	0.005	-4.109	0.001
F–L+|N+	-0.021	0.005	-4.109	?
F–L–	–	–	–	.50
F+L+	–	–	–	–

Significance of residualized factors on reading time.

Positive t-score: inhibition

Negative t-score: facilitation

Evaluation: Semantic Factors

Corpus: Reannotated WSJ

- Remove sentences with modifier embeddings [Pynte et al., 2008]

For example:
The CEO sold [[the shares] of the company]

Evaluation: Semantic Factors

Model	coeff	std err	t-score
Canonical	-0.040	0.010	-4.05
Other	-0.017	0.004	-4.20

Significance of residualized factors on reading time.
Positive t-score: inhibition
Negative t-score: facilitation

To achieve convergence, residualization was used

Conclusion

Results

- Described incremental semantic dependency parser
- General metrics are not hurt by semantic calculation
- Semantic metrics predict reading times better than syntactic
- Replicated negative integration cost without FG confound
- Failed to find support for maintenance cost

Fin

Thanks to Elliot Schumacher (and viewers like you)!
Questions?

Extras 1: Probabilistic Formulae

$$\mathsf{P}_{\phi_\ell}(\text{`}-\text{'}\ r^F \mid \langle i,c\rangle\ \langle j,d\rangle) \overset{\text{def}}{\propto} \mathsf{E}_{\gamma_\ell^*}(c \overset{0}{\rightarrow} d\ ...) \cdot \textstyle\sum_x \mathsf{P}_\gamma(d \rightarrow x) \cdot [\![ r^F = \langle i, \text{`id'}, j\rangle]\!] \quad \text{(1a)}$$

$$\mathsf{P}_{\phi_\ell}(\text{`}+\text{'}\ r^F \mid \langle i,c\rangle\ \langle j,d\rangle) \overset{\text{def}}{\propto} \mathsf{E}_{\gamma_\ell^*}(c \overset{+}{\rightarrow} d\ ...) \cdot \textstyle\sum_x \mathsf{P}_\gamma(d \rightarrow x) \cdot [\![ r^F = \langle \text{`}-\text{'}, \text{`}-\text{'}, \text{`}-\text{'}\rangle]\!] \quad \text{(1b)}$$

$$\mathsf{P}_{\lambda_\ell}(\text{`}+\text{'} \mid \langle i,c\rangle\ \langle j,d\rangle) \overset{\text{def}}{\propto} \textstyle\sum_{c',e} \mathsf{E}_{\gamma_\ell^*}(c \overset{0}{\rightarrow} c'\ ...) \cdot \mathsf{P}_{\gamma_{B,\ell}}(c' \rightarrow d\ e) \quad \text{(2a)}$$

$$\mathsf{P}_{\lambda_\ell}(\text{`}-\text{'} \mid \langle i,c\rangle\ \langle j,d\rangle) \overset{\text{def}}{\propto} \textstyle\sum_{c',e} \mathsf{E}_{\gamma_\ell^*}(c \overset{+}{\rightarrow} c'\ ...) \cdot \mathsf{P}_{\gamma_{A,\ell}}(c' \rightarrow d\ e) \quad \text{(2b)}$$

$$\mathsf{P}_{\nu_\ell}(\text{`}+\text{'} \mid \langle i,c\rangle\ \langle j,d\rangle\ \langle j',d'\rangle\ \langle k,e\rangle) \overset{\text{def}}{=} [\![c,d,d' \in C \times \{\textbf{-g}\} \times C\ \wedge\ e \notin C \times \{\textbf{-g}\} \times C]\!] \quad \text{(3a)}$$

$$\mathsf{P}_{\nu_\ell}(\text{`}-\text{'} \mid \langle i,c\rangle\ \langle j,d\rangle\ \langle j',d'\rangle\ \langle k,e\rangle) \overset{\text{def}}{=} [\![c,d,d' \notin C \times \{\textbf{-g}\} \times C\ \vee\ e \in C \times \{\textbf{-g}\} \times C]\!] \quad \text{(3b)}$$

Extras 1: Probabilistic Formulae

$$\mathsf{P}_{\alpha_\ell}(\langle i',c'\rangle\ r^A \mid l\,\langle i,c\rangle\,\langle j,d\rangle) \overset{\text{def}}{\propto} \begin{cases}\text{if } l{=}\text{‘+’} : \sum_e \mathsf{E}_{\gamma^*_\ell}(c \xrightarrow{+} c' \ \ldots)\cdot \mathsf{P}_{\gamma_{A,\ell}}(c' \rightarrow d\ \ e)\\ \text{if } l{=}\text{‘–’}\ : [\![c'=d]\!]\end{cases}$$
$$\cdot \begin{cases}\text{if } l{=}\text{‘+’} \vee [d\,..\Rightarrow c'] \in \text{Ae–h,Me–h} : [\![i'=j]\!]\\ \text{if } l{=}\text{‘–’} \wedge [d\,..\Rightarrow c'] \in \text{Aa–d,Ma–d}\ : [\![i'=\mathbf{i_{Z+1}}]\!]\end{cases}$$
$$\cdot \begin{cases}\text{if } l{=}\text{‘+’} : [\![r^A=\langle i', \text{‘id’}, j\rangle]\!]\\ \text{if } l{=}\text{‘–’}\ : [\![r^A=\langle \text{‘–’},\text{‘–’},\text{‘–’}\rangle]\!]\end{cases} \tag{1}$$

$$\mathsf{P}_{\beta_{s,\ell}}(\langle k,e\rangle\ r^B \mid \langle i,c\rangle\,\langle j,d\rangle) \overset{\text{def}}{\propto} \mathsf{P}_{\gamma_{s,\ell}}(c \rightarrow d\ \ e)\cdot \begin{cases}\text{if } [d\ e \Rightarrow c] \in \text{Aa–d,Ma–d} : [\![k=i]\!]\\ \text{if } [d\ e \Rightarrow c] \in \text{Ae–h,Me–h}\ : [\![k=\mathbf{i_{Z+1}}]\!]\end{cases}$$
$$\cdot \begin{cases}\text{if } [d\ e \Rightarrow c] \in \text{Aa–d,Me–h} : [\![r^B=\langle k, V(e), j\rangle]\!]\\ \text{if } [d\ e \Rightarrow c] \in \text{Ae–h,Ma–d} : [\![r^B=\langle j, V(d), k\rangle]\!]\\ \text{if } [d\ e \Rightarrow c] \in \text{Fa–c} \quad\quad : [\![r^B=\langle \text{‘–’},\text{‘–’},\text{‘–’}\rangle]\!]\end{cases} \tag{2}$$

$$\mathsf{P}_{\kappa_\ell}(r^K \mid \langle i,c\rangle\,\langle i',c'\rangle\,\langle j,d\rangle\,\langle k,e\rangle) \overset{\text{def}}{=}$$
$$\begin{cases}\text{if } c{\in}C{\times}\{\textbf{-g}\}{\times}C \ \wedge\ \exists_{d'}\ d'\ \ e \Rightarrow c' \ \wedge\ [d \Rightarrow d'] \in \text{Ga–b} : [\![r^K=\langle i', V(d), i\rangle]\!]\\ \text{if } c{\in}C{\times}\{\textbf{-g}\}{\times}C \ \wedge\ \exists_{e'}\ d\ \ e' \Rightarrow c' \ \wedge\ [e \Rightarrow e'] \in \text{Ga–b} : [\![r^K=\langle i', V(e), i\rangle]\!]\\ \text{if } c{\in}C{\times}\{\textbf{-g}\}{\times}C \ \wedge\ \exists_{d'}\ d'\ \ e \Rightarrow c' \ \wedge\ [d \Rightarrow d'] \in \text{Gc} : [\![r^K=\langle i, 1, i'\rangle]\!]\\ \text{if } c{\in}C{\times}\{\textbf{-g}\}{\times}C \ \wedge\ \exists_{e'}\ d\ \ e' \Rightarrow c' \ \wedge\ [e \Rightarrow e'] \in \text{Gc} : [\![r^K=\langle i, 1, i'\rangle]\!]\\ \text{otherwise} : [\![r^K=\langle \text{‘–’},\text{‘–’},\text{‘–’}\rangle]\!]\end{cases} \tag{3}$$

Extras 1: Probabilistic Formulae

$$\begin{aligned} \mathsf{P}_{\sigma}(q_t^{1..N} \mid q_{t-1}^{1..N} x_{t-1}) &\stackrel{\text{def}}{=} \mathsf{P}_{\phi_\ell}(\text{`}-\text{'} \mid b_{t-1}^{\ell}\ x_{t-1}) \cdot \mathsf{P}_{\sigma'_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N}\ a_{t-1}^{\ell}) \\ &\quad + \mathsf{P}_{\phi_\ell}(\text{`}+\text{'} \mid b_{t-1}^{\ell}\ x_{t-1}) \cdot \mathsf{P}_{\sigma'_{\ell+1}}(q_t^{1..N} \mid q_{t-1}^{1..N}\ x_{t-1}); \quad \ell \stackrel{\text{def}}{=} \max\{\ell' \mid q_{t-1}^{\ell'} \neq \text{`}-\text{'}\} \end{aligned} \tag{4}$$

$$\begin{aligned} \mathsf{P}_{\sigma'_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a') &\stackrel{\text{def}}{=} \mathsf{P}_{\lambda_\ell}(\text{`}+\text{'} \mid b_{t-1}^{\ell-1}\ a') \cdot [\![ a = a_{t-1}^{\ell-1} ]\!] \cdot \mathsf{P}_{\beta_{\mathrm{B},\ell-1}}(b \mid b_{t-1}^{\ell-1}\ a') \cdot \mathsf{P}_{\sigma''_{\ell-1}}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b\, a') \\ &\quad + \mathsf{P}_{\lambda_\ell}(\text{`}-\text{'} \mid b_{t-1}^{\ell-1}\ a') \cdot \mathsf{P}_{\alpha_\ell}(a \mid b_{t-1}^{\ell-1}\ a') \cdot \mathsf{P}_{\beta_{\mathrm{A},\ell}}(b \mid a_t^{\ell}\ a') \cdot \mathsf{P}_{\sigma''_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b\, a') \end{aligned} \tag{5}$$

$$\begin{aligned} \mathsf{P}_{\sigma''_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b\, a') &\stackrel{\text{def}}{=} \mathsf{P}_{\nu_{\ell-1}}(\text{`}+\text{'} \mid a_{t-1}^{\ell-1}\ b_{t-1}^{\ell-1}\ a_{t-1}^{\ell}\ b) \cdot \mathsf{P}_{\kappa_{\ell-1}}(r^K \mid b_{t-1}^{n}\ b_{t-1}^{\ell}\ a'\ b) \cdot \mathsf{P}_{\sigma'''_{\ell-1}}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b) \\ &\quad + \mathsf{P}_{\nu_{\ell-1}}(\text{`}-\text{'} \mid a_{t-1}^{\ell-1}\ b_{t-1}^{\ell-1}\ a_{t-1}^{\ell}\ b) \cdot \mathsf{P}_{\kappa_{\ell-1}}(r^K \mid b_{t-1}^{n}\ b_{t-1}^{\ell}\ a'\ b) \cdot \mathsf{P}_{\sigma'''_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b) \end{aligned} \tag{6}$$

$$\mathsf{P}_{\sigma'''_\ell}(q_t^{1..N} \mid q_{t-1}^{1..N} a\, b) \stackrel{\text{def}}{=} [\![q_t^{1..\ell-1} = q_{t-1}^{1..\ell-1}]\!] \cdot [\![a_t^{\ell} = a]\!] \cdot [\![b_t^{\ell} = b]\!] \cdot [\![q_t^{\ell+1..N} = \text{`}-\text{'}]\!] \tag{7}$$

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